A NETWORK ANALYZER FOR SOLVING MINE-VENTILATION-DISTRIBUTION PROBLEMS

By G. E. McElroy

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G. E. McElroy[1]/

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INTRODUCTION

Economic solutions of problems of mine-ventilation improvement can be found by mathematical analyses of alternative methods of procedure, but, in the case of our older bituminous-coal mines, the airway network is usually so complex that mathematical solutions are too tedious to be practical. Recourse usually is made to extremely costly and uncertain trial-and-error procedures with the existing layout and equipment. The resulting errors often prove costly and sometimes create hazardous conditions. Both the economic and safety aspects of alternative methods of ventilation improvement may be rapidly and cheaply investigated with analogue computers.

An electrical analogue computer, designed and built especially for analyzing mine-ventilation-distribution problems, has been placed in service by the Bureau of Mines at its Pittsburgh, Pa., Experiment Station. It is a nonlinear, low-voltage, fluid network analyzer of a type developed by Malcolm S. McIlroy, professor of electrical engineering at Cornell University. It was designed in close cooperation with Professor McIlroy and built by the Standard Electric Time Co., Springfield, Mass. It is the seventh unit of this type to be placed in service and the first designed for mine airflow problems. The other six were designed for either water- or gas-distribution analyses. Three are much larger and more expensive units. The largest unit has a capacity of 20 sources, 576 mains, and 180 loads, or regulated-flow paths. The Bureau unit has a capacity of 5 sources, 128 mains, and 48 loads.

Analogue computors using linear resistor elements have been used extensively for analyzing gas-, water-, steam-, and electric-distribution systems. In the case of the latter, the results have direct application, as the resistances of wire distribution systems are also linear. However, for fully turbulent fluid flow the resistances to flow are nonlinear, and a tedious process of successive approximations is required in analyses of distribution networks. Direct results are obtained only when nonlinear resistors are used.

Tungsten filament lamps, operated by alternating current or direct current, approximate the square-law resistance characteristics of mine airflow over a large range below maximum, or rated, voltage; that is, the voltage drop varies approximately as the square of the current. An analogue employing commercial types of lamps, as used at the Central Research Station of the Netherlands State Mines, was described by Dr. Maas[2] in 1950, and others were built in England,[3] South Africa (Rand),[4] and elsewhere. As the information available on these devices indicated they were somewhat inflexible in use because of the difficulty of securing commercially available lamps of a sufficiently wide range of resistances, even with group arrangements, and because of the dangerously high overall voltages required for

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2/ Maas, W., [An Electrical Analogue for Mine Ventilation and Its Application to Ventilation Planning]: Geologie En Mijnbouw (The Hague), vol. 12, 1950, pp. 117-123.

3/ Scott, D. R., and Hinsley, F. B., The Solution of Ventilation Network Problems: Trans. Inst. Min. Eng. (London), vol. 3, 1951-52, pp. 347-371.

4/ Beadle, D. G., An Aid to Ventilation Calculations: Mine Vent. Soc. South Africa, vol. 6, No. 2, 1953, pp. 14-21.

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operation, a simpler resistance element was sought. The idea was conceived of avoiding both difficulties by using specially constructed low-voltage tungsten-filament lamps in a graduated series of constant resistances with an overall voltage requirement of 100 to 150 volts for networks and current requirements of 5 to 10 amperes.

It was late in the summer of 1952, while studying how such a device could be made with Bureau facilities, that the author first noted[5] Professor McIlroy's analogue. It was immediately realized that this was the answer to our requirements, and solution of problems on hand on his experimental analogue at Cornell University supported this conclusion. It was found that the original description of the instrument had appeared[6] in a waterwork's journal 2 years before and so had naturally escaped notice. A more recent paper[7] was about to appear, and three instruments of this type, built by the Standard Electric Time Co. of Springfield, Mass., were then in service and several others were in the planning stage.

As mine-ventilation networks differ in some respects from water- and gas-distribution networks for which previous analogues of this type had been designed, an intensive study of available ventilation survey data for complex bituminous-coal mine ventilation networks was made, and, in consultation with Professor McIlroy, essential requirements, required quantities, and special design features were developed. Specifications were drawn up in April 1953, a contract was let that June, and the analyzer was installed in mid-April of 1954.

THE FLUISTOR

The heart of this type of analyzer is a nonlinear resistor, known as a Fluistor, which is simply a custom-made low-voltage tungsten-filament lamp, which is available in a progressive series of resistance values ranging from about 0.05 to 250 in nominal steps of 5 percent. However, slight variations in manufacturing bring the variations in large groups down to 1 to 3 percent, and series arrangements required usually for the high-loss branches of a network enable these to be matched within about 1 percent. Although maximum rated voltage is 4.6 and about 12 volts is required to fuse the filaments, they are usually operated at an average of about 2.5 volts to avoid accidental overloading and to prolong their useful life. The Bureau analyzer has a complement of 350 Fluistors.

REGULATED-FLOW AND BOOSTER-PRESSURE CIRCUITS

Although completely automatic electronic current-flow regulators for loads are available, they add greatly to the cost and voltage requirements and were not considered necessary in the Bureau unit, which provides for semiautomatic control of 8 load units through "Amperite" tubes and manual control of the other 40 units.

Except for method of control, all load units are similar linear-resistance circuits and can be used interchangeably to represent mine intakes, exhausts, or regulated splits. Each circuit includes an ammeter for indicating flow.

5/ McIlroy, M. S., Analyzing Pipe Line Networks: Heat. Pip. and Air Cond., July 1952, pp. 100-103.

6/ McIlroy, M. S., Direct-Reading Electric Analyzer for Pipeline Networks: Jour. Am. Water Works Assoc., vol. 42, 1950, pp. 347-366.

7/ McIlroy, M. S., Gas Pipe Networks Analyzed by Direct-Reading Electric Analogue Computer: Am. Gas Assoc., Paper IMC-52-10, 1952, 15 pp.

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For the special purpose of representing underground fans, combinations of force and exhaust surface fans, and natural drafts, 4 of the 5 source circuits of the Bureau instrument are arranged as booster circuits, devices not previously incorporated in McIlroy analyzers, which can be inserted between any 2 points of a network to increase the voltage a required amount.

THE ANALYZER

The analyzer consists of three 42- by 96- inch panels mechanically and electrically interconnected, with the various elements mounted, for the most part, on the front of the panels and interconnected on the rear but with some essential elements mounted and interconnected on the rear, for which purpose the central section has a large hinged rear section. Figures 1 to 5 show the analyzer set for the solution of a moderately complex network problem embodying 30 branches, 20 regulated splits, 1 exhaust fan and outlet, 1 main intake, and 2 minor intakes.

The left, or network panel, is divided vertically into 4 separate rows of interconnected junctions and longitudinally into 2 separate blocks. End junctions between blocks have 3 receptacles and all others have 2. However, blocks and rows can be interconnected, either by cords or 2-prong plugs, so as to provide 6 receptacles between blocks or 4 between rows, in which case both junctions on the panel represent the same junction in the mine airflow network. For each junction 1 receptacle is required for plugging in across circuit points for voltmeter readings and 1 for interconnecting junctions between rows or blocks.

Between each pair of junctions on the front of this panel is a special spring-switch receptacle, which permits insertion of a matching plug for connecting the master ammeter to the circuit, as shown in figure 5. Direction of flow is determined by whether the white line on the top of the plug as shown is up or down when the deflection of the master ammeter needle is normal.

Sockets for Fluistors are permanently wired in series with the junctions and ammeter receptacles (switch normally closed) on the back of the network panel. These are standard lamp sockets and extend to holes in cover plates on which the sockets are suitably identified.

The front of the central panel is essentially a control panel and the rear a patching panel. A map panel of 20 by 30 receptacles occupies the upper section of the front and a similar patching panel is positioned directly back of it, with matching receptacles interconnected. The purpose of this map panel is discussed later.

Power is supplied to the analyzer at 115 a.c. volts from a separate 440-volt line through a transformer, lock-type switch, and voltage regulator and is converted to direct current for the single main "source" circuit by a plate-type rectifier mounted on the bottom rear of the central panel. Rectifier controls - power switch and variable-output autotransformer with venier adjustment - are located on the front of this panel below the shelf and permit the voltage to be increased smoothly from zero to the desired voltage, as required, to avoid overloading Fluistors.

Just below the shelf are the controls of 10 auxiliary rheostats, as required occasionally for smooth control of regulated currents. Above the shelf are 10 rheostat-ammeter combinations of various capacities for loads. Centrally located above this row is the master ammeter on the right and master voltmeter on the left, each with range and control switches alongside. Ammeter leads are brought out to

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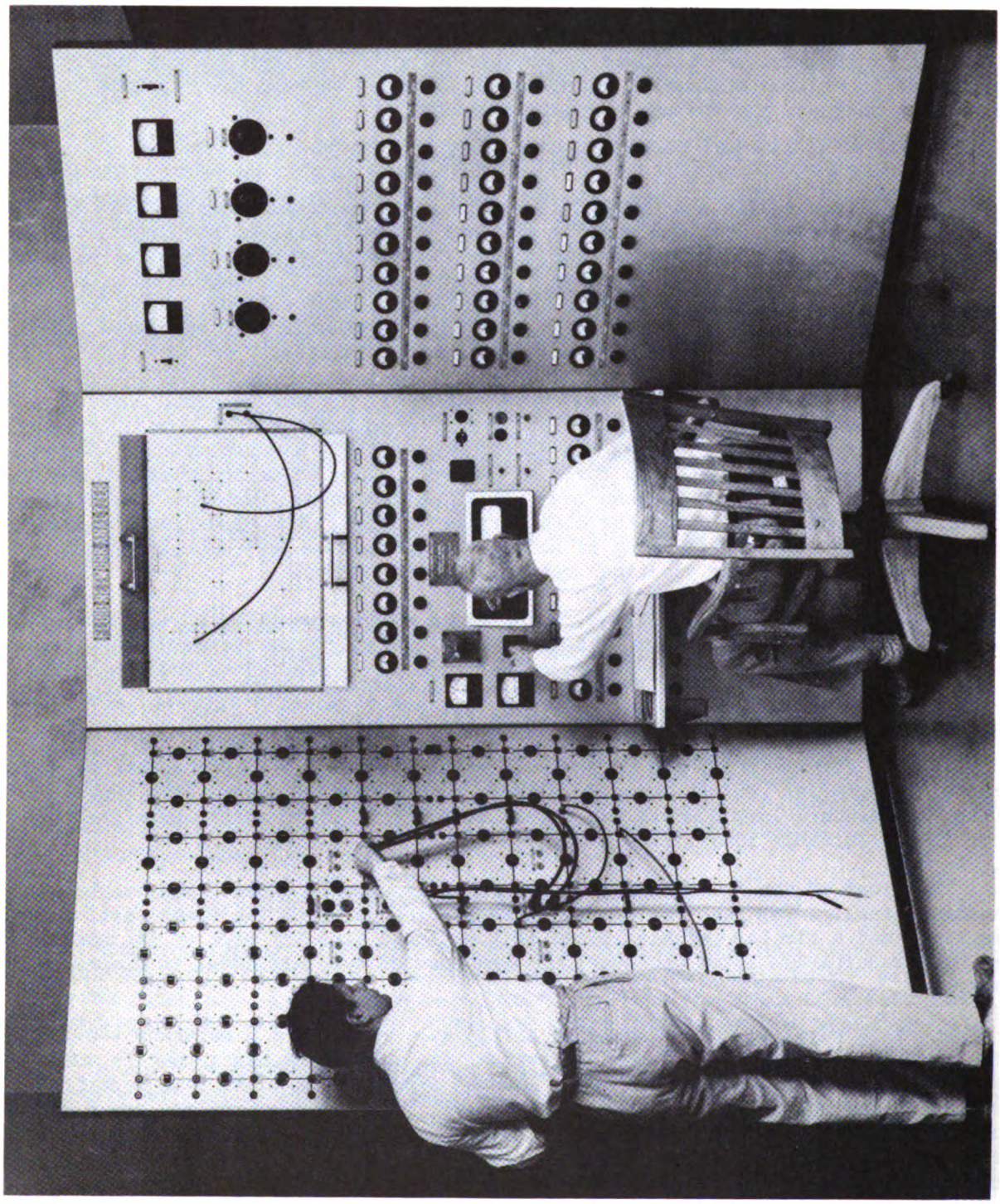

Figure 1. - Bureau of Mines analogue computer in operation.

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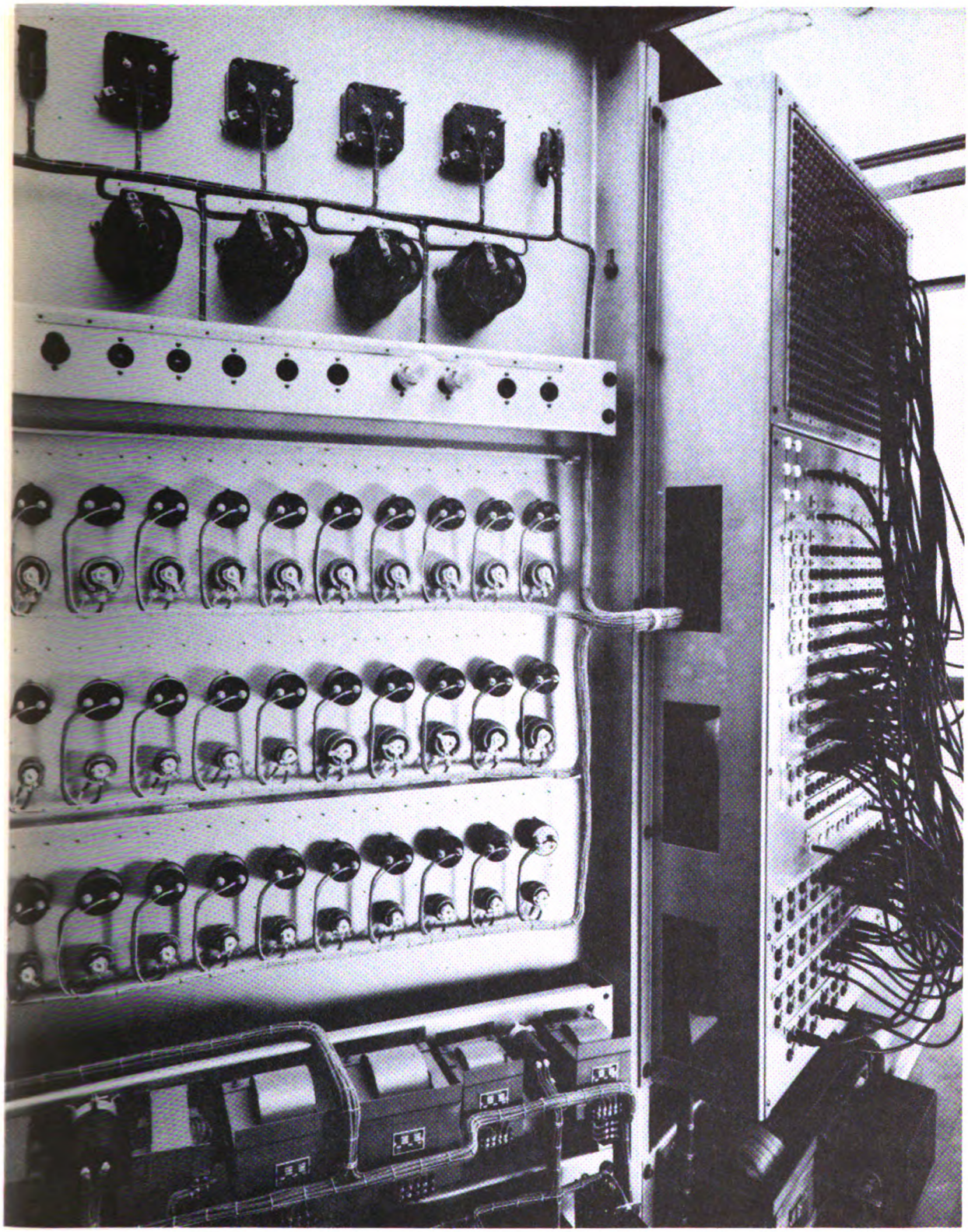

Figure 2. - Rear view of right and center panels.

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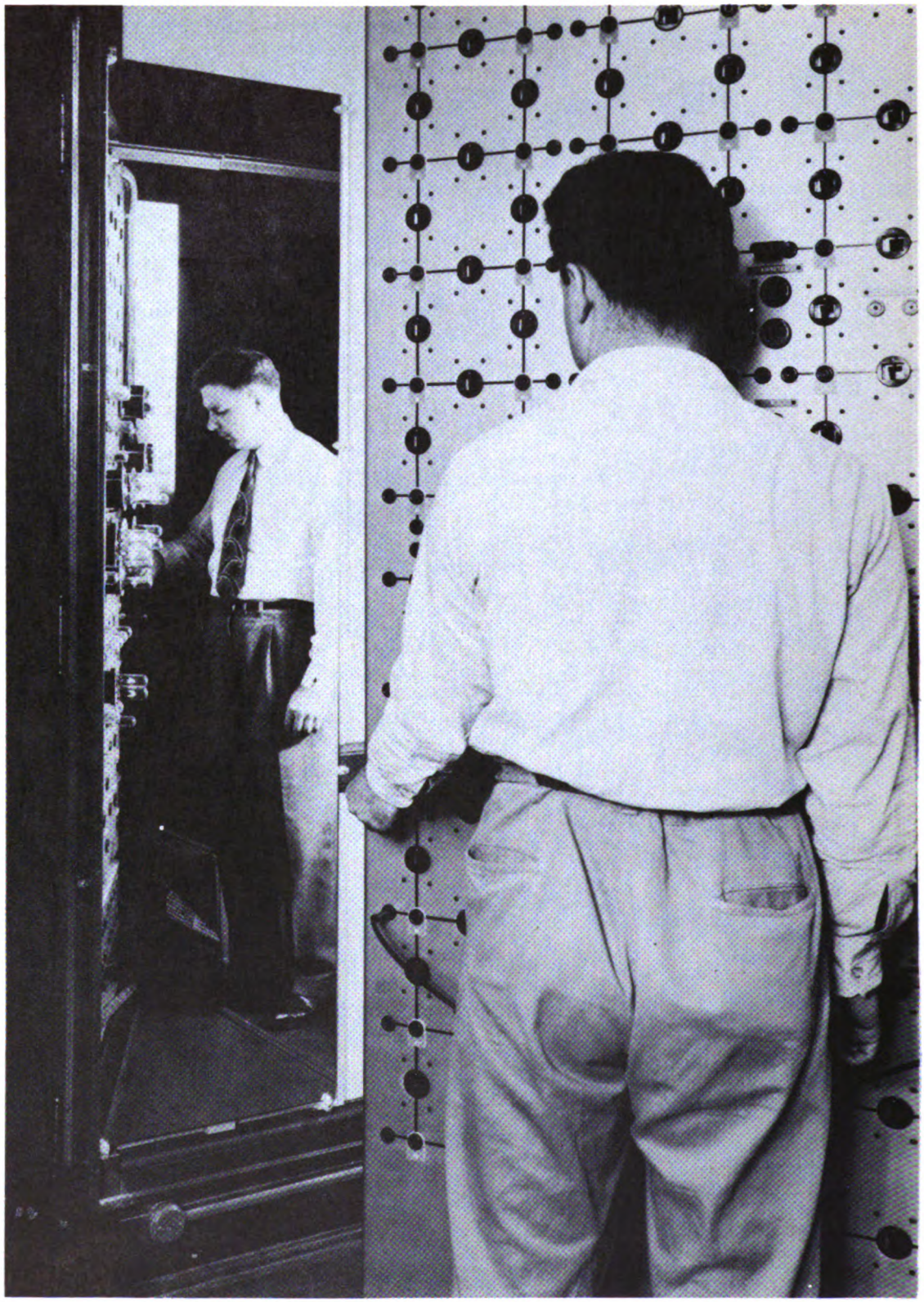

Figure 3. - Rear of left panel as seen through mirror mounted on adjacent wall.

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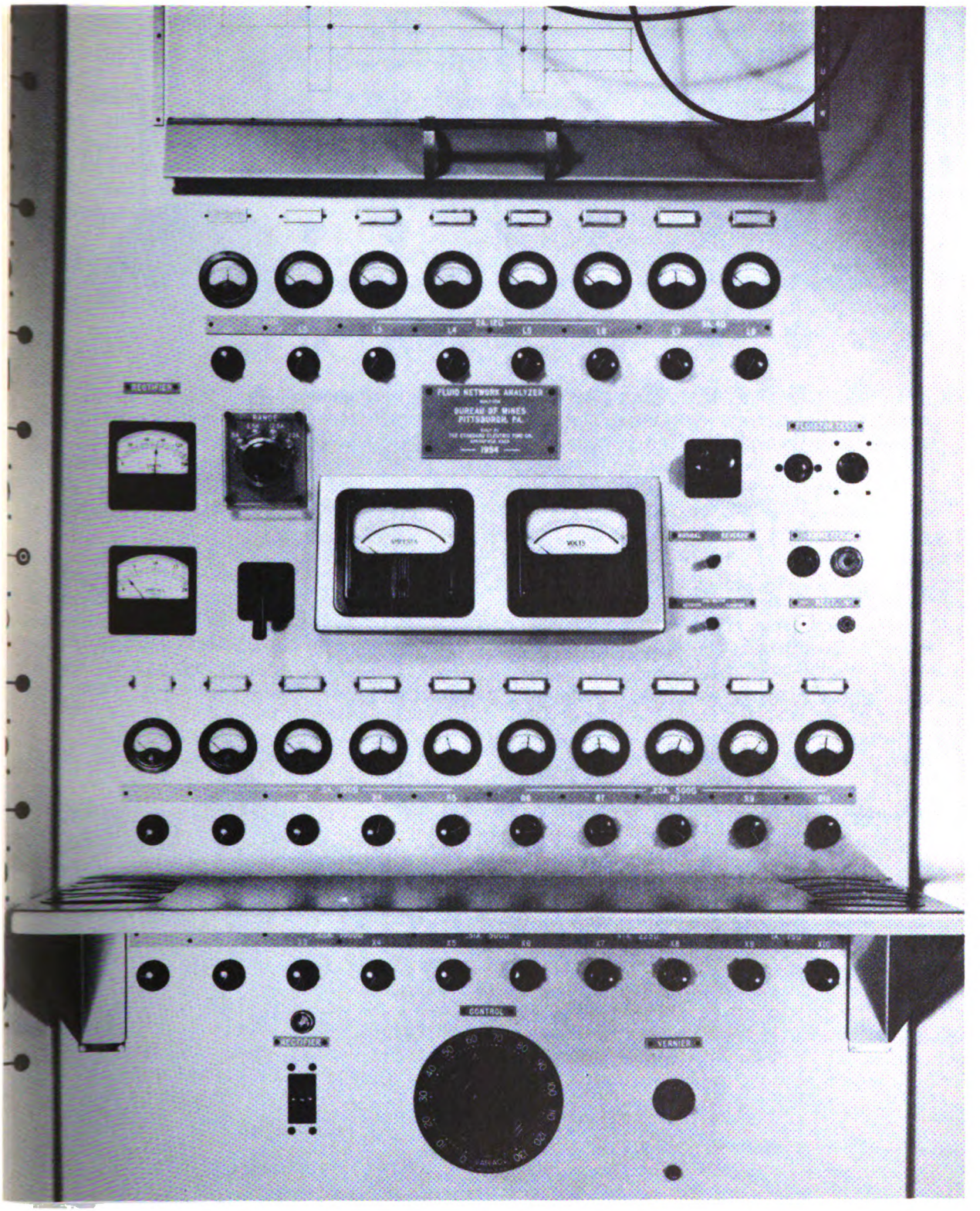

Figure 4. - Control features on lower part of center panel.

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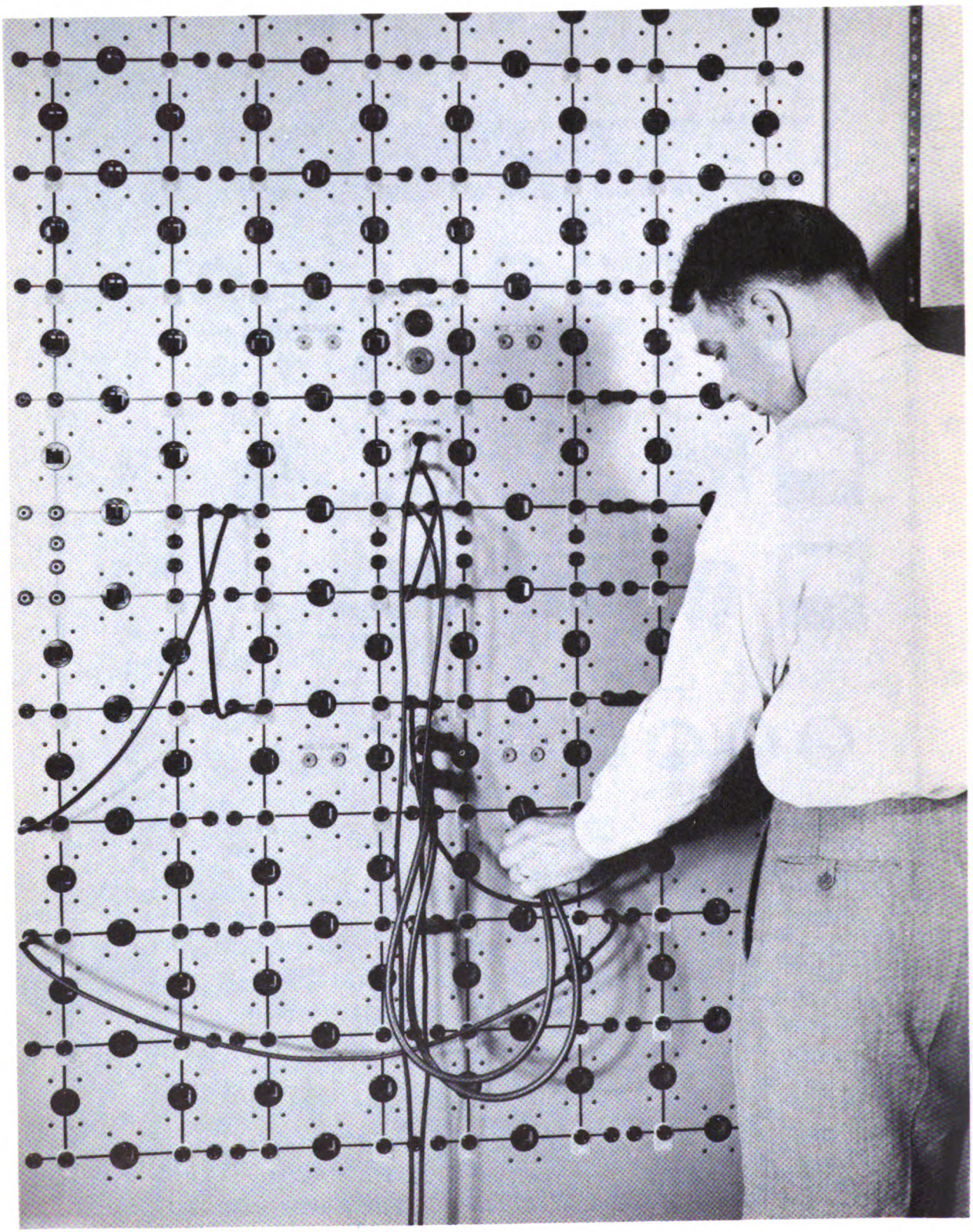

Figure 5. - Closeup view of section of left (network) panel.

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2 positions on the network panel - upper and lower center - and voltmeter leads to 1 position on the network panel and another alongside the map panel above.

Above the master meters is a group of eight rheostat-ammeter combinations for major loads, such as main intake or return currents. These circuits include single and parallel receptacles for semiautomatic current-limiting tubes, which are installed across the back of the right panel. "Amperite" tubes, "10" series, are used, and, as each operates only over a limited range, a complement of 50 has been provided.

To the right of the master voltmeter controls is a circuit for calibrating Fluistor tubes, which is energized, when in use, from 1 of the 4 separate booster circuits mentioned later.

Patch Panel

Permanent wiring is brought from all network junctions, from both positive and negative ends of all rheostat-ammeter circuits and auxiliary rheostats, and from both positive and negative ends of four booster circuits to pairs of receptacles mounted on a hinged panel attached to the rear of the control panel. This patch panel also has 12 taps to the positive side of the rectifier circuit and 12 to the negative side, providing for up to 12 intakes to, or outlets from, the network.

By means of the patch panel and flexible cord connections, as shown in figure 2, any point in the network can be connected to any point on the map panel, to any load circuit, or to the positive (inlet) or negative (outlet) side of the primary circuit, and load circuits and auxiliary rheostats may be interconnected in series and parallel arrangements. Points in the network can also be connected to each other on the patch panel, though in practice most of these point-to-point connections are made on the network panel itself, as shown in figure 1.

The right panel is entirely occupied, both front and rear, with 30 regulated-flow circuits and 4 booster circuits.

Booster Circuits

The booster circuits are required to represent pressure developed between two points in a network, as by an underground fan or natural draft. One of the two points could be either the positive or negative side of the primary circuit, as required, to simulate surface force and exhaust fans used in combination. These circuits do not supply current to the network but merely produce an increase in voltage, or electrical pressure, between two points. The voltage change is regulated by variable-output autotransformers on the incoming alternating current, which, passing through an isolation transformer, full-wave plate rectifier, and ripple filter, produces the desired change in voltage; this is indicated by a voltmeter wired into the circuit. All are 10-ampere units; 2 are 50-volt capacity (for fans), and 2 are 10-volt capacity (for natural drafts). Although the number of units is enough for coal-mine problems, it is not enough for many large multilevel and multifan metal-mine ventilation-network analyses.

Selection of Fluistors

The accuracy of results of analyses depends on matching Fluistor resistances to airway resistances. This not only involves ratios dependent on the units used

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but also the fact that mine airways have a second power law of resistance whereas Fluistors have a 1.85 power law. Proper correlation is obtained by the formula:

$$K_F = \frac{H^{.075} B R^{.925}}{G^{1.85}},$$

where

K_F = Fluistor coefficient in $V = K_F I^{1.85}$,
V = voltage drop across Fluistor,
I = current flow in amperes through Fluistor,
H = airflow pressure drop for section of airway,
B = volts per unit pressure-drop,
R = resistance coefficient for airflow in $H = RQ^2$,
Q = quantity of flow,
G = amperes per unit flow rate.

The airflow resistance coefficients in general use in mine ventilation are based on pressures in inches of water and airflows in 100,000 c.f.m. (cubic feet per minute) and the general range of values for sections of airways is about one-tenth the range of Fluistor coefficients available. Also, expected maximum pressures for mine-ventilation systems range from 5 to 10 inches, or less than one-tenth of the electrical pressures (160 volts d. c.) available. Though other scales can be used, the analyzer was designed for the preferred scales of B = 10 and G = 1, that is, for 10 volts representing 1 inch water pressure and 1 ampere representing 100,000 c.f.m. A simple graph, such as shown in figure 6, facilitates the determination of Fluistor coefficients from airflow resistance factors and pressures. Fluistors are then selected for each branch of a network on the basis of 1 tube for each 0.25 to 0.30 inch pressure drop, with 2 or more tubes in series where required for the largest pressure drops.

In operation, the number of tubes and the comparative brightness of their filaments serve as a visible indication of the high pressure-drop branches of a network.

Map Panel

The map panel that occupies the front of the upper part of the central panel is not required in analyses but is useful as a basis for discussing proposed changes and in demonstrating steps in analyses to observers. As the jacks of the 20 by 30 grid are on 1-inch centers, map diagrams can be made on standard cross-section paper. Holes punched in the diagram, at junctions and at points representing inlets and outlets, permit insertion of voltmeter plugs so that the pressure-drop can be measured across any pair.

Slip-on Scales for Master Meters

Both the master ammeter and the master voltmeter have four ranges each. Slip-on scales are provided for three different scale units for each range of each instrument, making it possible to read the results of analyses directly in cubic feet per minute and inches of water pressure rather than in amperes and volts. The slip-on scales are white on black and more easily read than the black-on-white scales of the instruments themselves.

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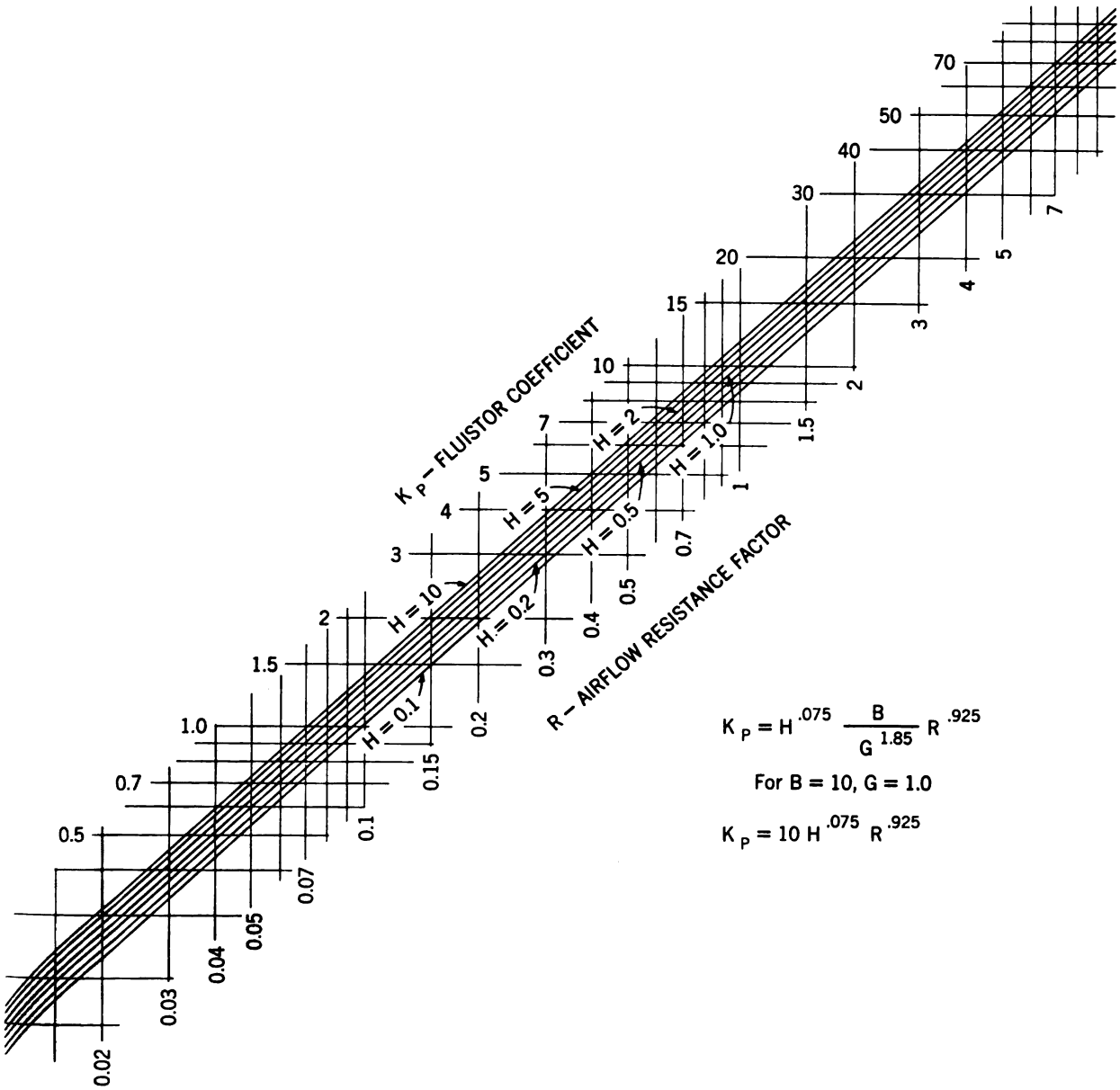

Figure 6. - Graph showing relation of Fluistor coefficient to airflow resistance factor for preferred scales of B=10 and G=1.0.

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APPLICATION

The primary purpose of this equipment is to aid in the solution of problems of mine-ventilation improvement where complex networks are involved and where the difference between a trial-and-error solution and an economical solution based on a study of alternative methods of procedure with this equipment may not only save large sums yearly, but also avoid the hazards that often develop after a change based on trial and error has been put into effect.

In designing initial mine layouts, ordinary algebra often suffices for calculating initial fan duties and changes in duty for successive stages of mine development. With free flow, somewhat extensive layouts can be calculated by simple algebra, but, with free-flow and regulated-flow branches combined, the solutions become difficult for comparatively simple networks. Recourse may then be made to a more difficult mathematical method of successive approximation for solving networks of any degree of complexity, which was developed in 1936, but was not brought to the attention of mining men until publicized[8/] in English mining journals in 1951.

Time Requirements

Regardless of whether solutions are found by mathematics or analyzer, the original data required for equal degrees of accuracy are the same in each instance. Considering the physical condition of mine airways, theoretical estimates are of little use except for new airways or motor roads, shafts, and other well-maintained openings. Accurate results require data furnished by accurate pressure and quantity surveys, which may be made by a number of methods but which, in any event, require considerable time - as much as 2 to 4 weeks for moderately complex systems.

Preparing data and setting up the analyzer to represent the existing distribution at the mine takes time, about as much as would be required for one solution of a simple network by mathematics, but only one-tenth to one-twentieth as much as for complex networks. But, whereas the investigation of each alternative by mathematics requires as much time as the original solution, the analyzer gives successive solutions at short intervals - approximately 1 hour, for example, for one that would otherwise take a week or more. One of the major advantages of the analyzer method is that qualitative solutions are often apparent at a glance through changes in brightness of Fluistor filaments and flow changes indicated by the ammeters. These furnish leads as to what changes may be made to effect desired results, a form of analysis that is virtually impossible to make mathematically.

Accuracy of Results

The absolute accuracy of results depends primarily on the accuracy of the data supplied for the analysis. But, whereas inaccuracies in original assumptions may carry through to final solutions by mathematical methods, similar inaccuracies are eliminated in analyzer solutions as currents are automatically balanced at junctions and pressures around loops are likewise balanced. Reported data for similar analyzers indicates that results within a maximum of 3 percent of calculated values may be obtained. Data for two complex networks, for which field-survey data had been accurately balanced by mathematical methods, were duplicated on the analyzer.

8/ Scott, D. R., and Hinsley, F. B., Ventilation Network Theory: Coll. Eng., vol. 28, 1951, pp. 67-71, 159-166, 229-235, and 497-500.

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About 90 percent of the pressure and quantity observations, including all of major importance, checked within 1 percent. The others varied up to a maximum of about 3 percent for pressures and less than 2 percent for quantities. These figures can be taken to represent the to-be-expected relative accuracies of analyses. The absolute accuracy of results will, as said before, depend primarily on the accuracy of mine-survey data.

Pressure differences may be rapidly determined by absolute-pressure methods, but good instruments, skilled technique, and steady atmospheric and mine airflow conditions are required, so that good surveys can be made only when the mine is idle and atmospheric conditions are right. As the least unit of measurement is usually 1 foot of air column, or about 0.014 inch water, the method is applicable only to the main airways and not to the network of low-velocity flow comprising operating sections. However, the net overall pressure difference on such sections is all that is needed for most analyses. Quantity surveys require considerable time but less skilled technique. Under conditions as they now exist in most bituminous-coal mines, many measurements have to be made in sections of airways where the physical conditions of the airway, or of the airflow, preclude accurate measurement. Results of surveys must necessarily be "faired" up, that is, quantities at junctions must be equalized in accordance with the surveyor's judgment of the relative accuracy of the quantity measurements involved.

Actually, all that is required to set up the analyzer for operation is the actual resistance values, or relations of pressure to quantity for the component parts of the system. Actual pressure differences and quantity distribution can then be determined by analysis for any desired rate of total flow and any included regulated splits.

CONCLUSION

The direct electrical-analogy method of analyzing mine-ventilation networks, such as is provided by equipment recently installed at the Pittsburgh Station of the Bureau of Mines, is a convenient, rapid, and accurate means of studying mine-ventilation-distribution systems. Changes to represent alternate plans of distribution or operating features can easily be made and their effects measured rapidly. Performance can be analyzed in detail, and alterations can be planned for maximum economy.

The operation of this method is easily understood, and any person with a technical background can be trained to operate the analyzer in a short time. The translation of mine-survey data to skeleton diagram form, then to looped network form, then to analyzer network form, and the correlation of the results and implications of analyses require an experienced technical operator with mining experience, preferably a mine-ventilation specialist.

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